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Published in:
Applied Physics Letters

DOI:
10.1063/1.125893

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Citation: Appl. Phys. Lett. **76**, 780 (2000); doi: 10.1063/1.125893
View online: https://doi.org/10.1063/1.125893
View Table of Contents: http://aip.scitation.org/toc/apl/76/6
Published by the American Institute of Physics

APPLIED PHYSICS LETTERS VOLUME 76, NUMBER 6 7 FEBRUARY 2000

Geometric heat trapping in niobium superconductor–insulator–superconductor mixers due to niobium titanium nitride leads

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(Received 14 October 1999, accepted for publication 13 December 1999)

We analyze the current–voltage characteristics of a Nb superconductor–insulator–superconductor mixer with NbTiN leads to identify the heating processes in this device. We argue that the electron–electron interaction is much faster than the electron–phonon interaction, and show that the heat flow to the bath temperature is limited by the electron–phonon interaction time in the junction. A solution is suggested to considerably reduce the heating. © *2000 American Institute of Physics.* [S0003-6951(00)03106-5]

Niobium superconductor–insulator–superconductor (SIS) tunnel junctions are currently the most promising mixers for radio-frequency detection around 1 THz. It is well known that SIS mixers can operate up to twice their frequency gap.[1] However, radiation at energies higher than the frequency gap is absorbed through Cooper pair breaking in Nb,[2] thus increasing the total mixer noise. In view of minimizing radio-frequency (rf) losses at frequencies beyond 700 GHz, a structure is investigated which uses NbTiN as material for the leads and tuning structure of the Nb junction. NbTiN has been shown to be a promising material as it combines a higher-frequency gap with a low resistivity and, therefore, ensures low rf losses for frequencies up to 1.2 THz.[3,4] The direct current (dc) current–voltage ($I-V$) curves of these devices show a negative slope of the quasiparticle current jump at the Nb gap, commonly referred to as backbending. A strong dependence of the energy gap reduction on the rf pumping level is also observed. These facts point to strong heating effects taking place in the device. Although heating at higher voltages has been reported before in all-Nb mixers,[5] the effect was not as severe. Heating was also observed in Nb junctions with NbN leads[6] and, although not analyzed, was attributed to the presence of the Nb/NbN interface. The implications of this heating effect on the mixer performance can be important. The depression of the energy gap corresponds to a reduction in the maximum operating frequency of the mixer. In addition, heating is also believed to degrade the mixer performance. Therefore, it is imperative to understand the processes of heating. In order to achieve this, we have measured and analyzed dc $I-V$ curves at different bath temperatures.

The layout of the device is sketched in Fig. 1(a). The Nb junction is sandwiched between two NbTiN leads. These leads, in combination with an insulator SiO_2 layer, form a stripline functioning as an integrated tuning circuit for the mixer. The device is a standard $Nb/Al_xO_y/Nb$ junction with an area of $0.6\,\mu m^2$. The thickness of both Nb electrodes is 90 nm. The critical current density is $12\,kA/cm^2$. The top and bottom NbTiN leads are 400 and 280 nm thick, respectively. The critical temperatures of Nb and NbTiN in the device were measured to be 9.1 and 14.2 K. Device fabrication is described elsewhere.[3]

The energy diagram corresponding to the device is schematically shown in Fig. 1(b). The Josephson current is suppressed by a magnetic field. When the system is biased at the gap voltage V_{gap}, electrons tunnel through the barrier to fill the available states in the counterelectrode giving rise to quasiparticles. The larger energy gap of NbTiN acts as a barrier and seemingly prevents any further progress of the quasiparticles into the leads. However, Andreev reflection allows a quasiparticle to enter NbTiN by forming a Cooper pair and giving rise to a hole traveling in the opposite direction. Since this process does not transport energy, one obtains a situation in which charges are transported into the leads but energy is left behind in the junction. The symmetrically identical process occurs for holes. As a result, the quasiparticle temperature is expected to rise in both electrodes. *The overall pro-*

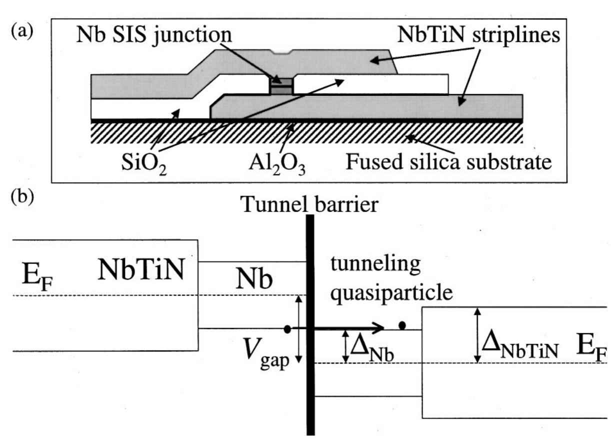

FIG. 1. (a) Sketch of the cross section of a Nb SIS junction with NbTiN striplines. (b) Energy diagram showing the relative energy gaps of Nb and NbTiN under the application of a bias voltage V_{gap} equal to the gap voltage of Nb.

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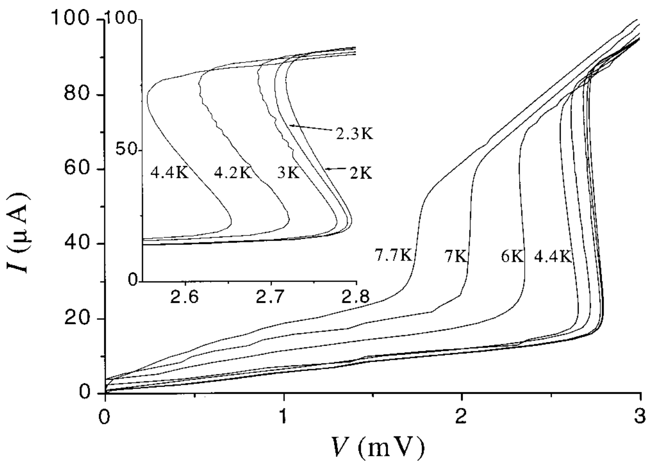

FIG. 2. dc $I-V$ characteristics of a Nb junction with NbTiN striplines for different bath temperatures. The inset zooms in on the backbending feature of the low-temperature curves.

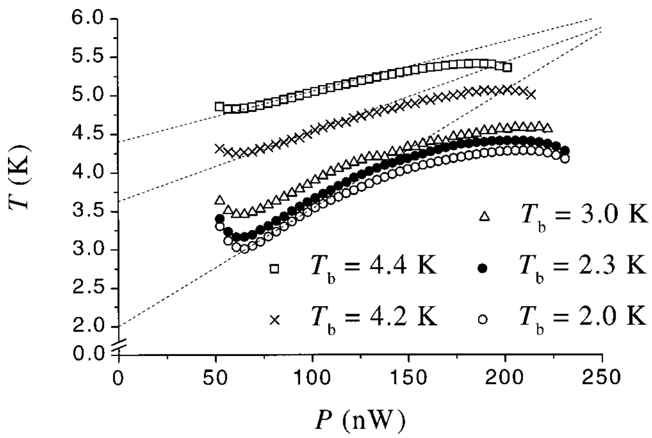

FIG. 3. T as a function of dc power for a selection of bath temperatures. Three linear fits are also shown, whose slope and y-axis intercept give α^{-1} and T_b, respectively.

cess can, therefore, be described not as quasiparticle trapping, but as a trapping of heat in the junction caused by the geometrical arrangement of the different materials constituting the mixer.

The dc $I-V$ characteristics are measured with a four-point setup in the current bias mode. The device is immersed in liquid He for temperatures at and below 4.2 K while for higher temperatures the device is placed in a vacuum can. The results are shown in Fig. 2. For the curves from 2 to 6 K, the backbending feature at the gap voltage can be clearly seen. It can be noted that this feature becomes weaker as the bath temperature increases and is absent for the 7 and 7.7 K curves. The backbending data points can be translated into temperature data using standard Bardeen–Cooper–Schrieffer (BCS) theory. The following equation is used to numerically compute the energy gap Δ as a function of temperature:[7]

$$\frac{1}{N(0)\beta}=\int_0^{\hbar\omega_c}\frac{\tanh[(2kT)^{-1}\sqrt{\epsilon^2+\Delta^2}]}{\sqrt{\epsilon^2+\Delta^2}}\,d\epsilon, \tag{1}$$

where $N(0)$ is the density of states at the Fermi level, β is the BCS interaction constant, and $\hbar\omega_c$ is the Debye frequency and is much greater than kT_c, where T_c is the critical temperature of Nb. In Eq. (1) it should be appreciated that T is the temperature of the electrons. Furthermore, we disregard the gap voltage smearing effect on the determination of the energy gap from the backbending data. Plots of the electron temperature as a function of dc power are shown in Fig. 3. The amount of heating occurring in the junction can be clearly estimated. At a bath temperature of 4.2 K, for instance, the electron temperature can rise up to about 1 K for an applied dc power of 200 nW.

The use of Eq. (1) implies that the quasiparticles are at an equilibrium temperature, i.e., that there is a sufficient interaction to smear out the energy dependencies resulting from the tunneling processes. This means that the electron–electron interaction is significantly strong. As it turns out, experimental values for τ_{ee} in Nb are difficult to obtain and are currently not available in the literature for 90-nm-thick Nb films. Furthermore, the ongoing debate on the validity of current theories,[8] which predict values for τ_{ee} that are three orders of magnitude larger than those recently obtained by experiment,[9,10] strongly discourages the use of theoretical estimates. Therefore, we resort to experimental values obtained for both electron–electron and electron–phonon relaxation times in Nb dirty thin films by Gershenzon *et al.*[11] as being $\tau_{ee}\approx 0.1$ ns and $\tau_{eph}\approx 1$ ns at 4.2 K. We shall here assume that these values also apply to our films and conclude that the quasiparticle system is at equilibrium. Additional support is provided by a study on dc heating in full Nb mixers[5] where the condition $\tau_{ee}\ll\tau_{eph}$ is likewise assumed, yielding predictions that agree well with experiment.

Although heating can be estimated from Fig. 3, one needs to understand the heat flow process. This is usually described by a heat balance equation which takes account of both the diffusion and phonon cooling processes.[12] Since diffusion cooling is absent here, the heat balance equation describing our system is then simply

$$P=\alpha(T^n-T_b^n), \tag{2}$$

where P is the dc power in the junction; T and T_b are the electron and bath temperatures, respectively; and n is an integer which depends on the model used. For simplicity, we shall assume $n=1$. The heat transfer coefficient α is determined by the heat flow bottleneck which we presently intend to determine. Two steps are involved in the heat transfer. First, energy must be exchanged between the electron and the phonon systems. Second, the phonons transfer the thermal energy from the junction to the bath. Let us first consider the case where the bottleneck is between the electrons and the phonons. In this case, α is given by

$$\alpha=\frac{VC_e}{\tau_{eph}}, \tag{3}$$

where C_e is the electron heat capacity and V the junction volume. If, however, the bottleneck is between the phonons and the bath and assuming a good phonon match between Nb and NbTiN, this bottleneck reduces to the Kapitza resistance at the substrate. In this case, α should increase when the device, initially in a vacuum, is immersed in liquid He.[13] A further enhancement is expected at the liquid/superfluid transition of He.[12]

Using Eq. (2), linear fits to the electron temperature plots can be obtained to extract values for α and the bath temperature. The slope of the linear fit is inversely proportional to α.

The curve at $T_b = 4.4\,\mathrm{K}$ was taken in a vacuum whereas $T_b = 4.2\,\mathrm{K}$ has the device in liquid He. If the Kapitza resistance were the bottleneck, the slope at $T_b = 4.4\,\mathrm{K}$ should be larger than the one at $T_b = 4.2\,\mathrm{K}$. In fact, the opposite trend is observed. Similarly, the curves at $T_b = 2.3\,\mathrm{K}$ and $T_b = 2\,\mathrm{K}$ mark the transition between liquid and superfluid He and one also expects a slope decrease. Clearly, hardly any change is observed and we conclude that the Kapitza resistance is negligible. The linear fits can also be used to check the agreement with experiment. We can now use Eq. (3) to estimate α. At 4.2 K, the heat capacity for bulk superconducting Nb (Ref. 14) is $2000\,\mathrm{J/K\,m^3}$ so the estimated α is about $2\times 10^{-7}\,\mathrm{W/K}$. This value agrees surprisingly well with $10^{-7}\,\mathrm{W/K}$ obtained from the linear fit. The bath temperatures are obtained from the intersection of the linear fit with the y axis and also show a good agreement with the measured values, as can be seen for, say, the $T_b = 4.4\,\mathrm{K}$ and $T_b = 2\,\mathrm{K}$ curves in Fig. 3.

A few points should be added regarding the applicability of the linear fit. First, Eq. (2) need not be linear in n. Indeed, the curves in Fig. 3 do seem to deviate from the linear behavior, especially for low bath temperatures. However, it is difficult to say that this behavior is due to a nonlinearity rather than, say, the temperature dependence of α. In fact, α is expected to decrease with temperature due to the exponential increase with temperature of τ_{eph}. Furthermore, the gap voltage smearing was not taken into account in the determination of $T(P)$ but is known to increase with temperature.[15] The smearing adds to the negative slope of the backbending, reducing its sharpness, and can eventually dominate. This explains why the backbending disappears at high temperatures—though the temperature dependence of α must also contribute to the weakening of the backbending at lower temperatures. Taking a typical smearing into account, estimated from a device with negligible heating, we obtain a temperature rise about 50% more severe than previously estimated.

Backbending has also been reported for tunnel junctions where an energy gap discontinuity is absent. This was observed for both Sn (Ref. 16) and Al (Ref. 17) SIS junctions. In these cases, the gap voltage depression is explained by invoking, for instance, a nonequilibrium number density for the quasiparticle subsystem.[16] It follows that the recombination time of the electrons plays a major role in modeling the backbending feature. As the recombination process requires that pairs of quasiparticles interact—an event which is due to become rarer as lower temperatures make quasiparticles less available—it is found that the gap depression is larger for lower bath temperatures. However, the gap depression in our junctions increases with bath temperature, as can be qualitatively observed in Fig. 2 for curves up to 4.4 K—above 4.4 K gap smearing dominates. Furthermore, this behavior qualitatively agrees with Eq. (2). Hence, quasiparticle recombination should have a minor influence.

In conclusion, dc heating in Nb SIS junctions with NbTiN striplines can be understood to be a heat flow from the electron bath to the He bath limited by the electron–phonon interaction. Since the Kapitza resistance is negligible, heating cannot be eliminated by inserting a layer of normal conductor between the bottom lead and the substrate. However, in the light of our understanding, one sees from Eq. (3) that a possible way to increase α, thereby reducing heating, is to increase the junction volume V. This should be done without affecting the junction size so as not to change the junction resistance. It is interesting to consider whether the insertion, say, of a gold layer between the junction and leads would be beneficial. The absence of an energy gap and an even smaller electron–electron interaction time in Au (Ref. 10) means that the electron temperature would be the same in both Nb and Au. Assuming, further, an excellent phonon match for the Nb–Au–NbTiN system, one would obtain a parallel heat transfer from the two materials so that the effective heat transfer coefficient would be the sum of the heat transfer coefficients for Nb and Au, respectively. At 4.2 K the heat capacity of Nb (Ref. 14) is about an order of magnitude larger than for Au,[18] but so is the electron–phonon interaction time.[19] Hence, adding the same volume of Au to the Nb would double the effective α. However, the same improvement is more practically obtained by simply doubling the volume of Nb.

The authors gratefully acknowledge helpful discussions with P. Dieleman and G. de Lange. This work was partly supported by the European TMR network for Terahertz electronics (INTERACT).

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